• How can a big group of UVA students talk at the same time on the same frequency using the iPhone?

MODULE 5: Communicating with the iPhone

- Amplitude modulation and demodulation
- Amplitude shift key, frequency shift key and phase shift key
- Frequency modulation
- Cellular communications
- Code Division Multiple Access
- CDMA v. FDMA v. TDMA
- CDMA in detail
- Circuit switching
- Packet switching
- The Internet
- Packet level error detection on the Internet
Modulation

- Modulation (*informally*): fitting a signal in a channel.
- We’re building up to the modulation approach of the iPhone. First, we’ll start with amplitude modulation.

- A common problem is: the **message bandwidth** does not match the **channel bandwidth**.
  - Consider a music signal: *mandolin.wav*
Close-up of high frequency components:

- Spectrum has a 20KHz bandwidth.
- We could broadcast this as an EM wave in the same frequency range – this is called baseband communication.
  
  **EX**: traditional analog phone line (300 – 3300 Hz)
  - Transmitting at baseband prevents others from doing the same.
  - There are poor attenuation characteristics at baseband.
  - And this is wasteful – consider the available spectrum…

*allocation.pdf*
Consider a digital signal – modeled by a square wave at 125 Hz.

- The spectrum has several high frequency components due to abrupt transitions.
- Cutting off high frequency components results in attenuation and logic delay due to smoothing of the transitions.
• We need a way to transform the information so that it does not use as much bandwidth.

• These difficulties can be overcome with modulation.

• Modulation can be considered the systematic alteration of a waveform (that we will call the carrier) by the message.

Amplitude Modulation (AM)

$f_c$: carrier frequency

**Carrier Wave**

$$x_C(t) = A_C \cos(2\pi f_C t)$$
• Modulation signal (=message) scaled between -1 and +1:

\[ -1 \leq x_m(t) \leq 1 \]

• Basic idea of AM: use the modulation signal to modulate the amplitude of the carrier wave.

\[ x_{AM} = x_c(t)[1 + m x_m(t)] \]

where \( m \) is the modulation index, \( 0 < m \leq 1 \)
AM Signal

\[ x_{AM}(t) = x_C(t) \times [1 + mx_m(t)] \]
\[ x_{AM}(t) = x_C(t) \times [1 + mx_m(t)] \]
\[ x_{AM}(t) = x_C(t) \times [1 + mx_m(t)] \]
\[ x_{AM}(t) = x_C(t) \times [1 + mx_m(t)] \]

\[ m = 1.5 \]

Envelope \( \neq [1 + mx_m(t)] \) when \( m > 1 \)
Tone Modulation

\[ x_m(t) = \cos(2\pi f_m t) \]
Trigonometric Identity:

\[ \cos \alpha \times \cos \beta = \frac{1}{2} \times [\cos(\alpha + \beta) + \cos(\alpha - \beta)] \]

\[ x_{AM}(t) = x_C(t) \times [1 + m x_m(t)] \]

\[ = A_C \cos(2\pi f_C t) \times [1 + m \cos(2\pi f_m t)] \]

\[ = A_C \cos(2\pi f_C t) + [mA_C \cos(2\pi f_C t) \times \cos(2\pi f_m t)] \]

\[ = A_C \cos(2\pi f_C t) + \frac{mA_C}{2} [\cos(2\pi (f_C + f_m) t) + \cos(2\pi (f_C - f_m) t)] \]
\( x_m(t) = \cos(2\pi f_m t) \)

\( x_C(t) = \cos(2\pi f_C t) \)
$x_{AM}(t) = A_C \cos(2\pi f_C t) \times [1 + m \cos(2\pi f_m t)]$

- Significance: the information carried by the message has been shifted in frequency – it now appears at $f_c + f_m$ and $f_c - f_m$. 
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<thead>
<tr>
<th>Frequency</th>
<th>Station</th>
<th>City/State</th>
<th>Type</th>
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<td>970 WAMD</td>
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<td>ethnic/Spanish/Chinese</td>
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<tr>
<td>1690 WPTX</td>
<td>LEXINGTON PARK MD</td>
<td>talk/nostalgia</td>
<td></td>
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</tbody>
</table>

Spacing = 10 KHz; Message Bandwidth = 5 KHz (each station has 10KHz)
• System works by allocating 10 KHz portions of the spectrum to different stations.

• The radio broadcaster’s voice may be sensed by a microphone, lowpass filtered at 5KHz (why?), modulated (multiplied by the carrier cosine wave), amplified, and sent through the airwaves via antenna.

• At receiver, the antenna receives the signal and amplifies. Using a tuner, the frequency range from one station is accepted, others rejected (rabbit trail: a band pass filter).
  o The signal must then be **demodulated**. This means that the signal needs to be returned to the original frequency range (0 to 5KHz in the AM case).
  o Demodulation in AM is easy. Recall that the AM signal spectrum has an envelope that is a copy of the message spectrum.
  o Let’s look at one conceptual way of demodulating the AM signal (recovering the message). Then we’ll discuss the “real” way.
Envelope Detection

Received AM Signal
Envelope Detection

Find Peak Values
Envelope Detection

Interpolate Peak Values
Envelope Detection

Subtract DC offset
Demodulation of AM: Synchronous Detection

- Since the AM spectrum has a “copy” of the original message spectrum, we can “move” the message spectrum back to its original frequency band.
  - How? Well, we’ve been moving frequency components by multiplying with a cosine function.

- Multiplication (modulation) by the carrier wave (cosine function) will return this copy to the original range.

### Science of Information Fundamental Tenet X

A (bandlimited) baseband signal can be modulated and demodulated by multiplying the signal with a sinusoid operating at carrier frequency.

In the above, modulated means "transferred in the frequency domain to a new center frequency (the carrier frequency)."

AND

Demodulated means "transferred back to baseband (centered at d.c. or zero frequency)."
Since there are two copies of the message spectrum in the AM signal, we’ll get one copy on the left side of 0-frequency (DC) and one copy on the right side.

- These are called the lower side band (LSB) and upper side band (USB)
- All the signal information is in both the LSB and USB.
- Why not just transmit and receive one of these, saving half the bandwidth?
- ANS: You can, it’s called single side band (SSB) transmission (used in shortwave, TV, etc.)
- Need more sophisticated receiver to demodulate.
\[ x_{AM}(t) = A_C \cos(2\pi f_C t) \times [1 + m \cos(2\pi f_m t)] \]
\[ \cos(2\pi f_C t) \times x_{AM}(t) \]

\[ \cos(2\pi f_C t) x_{AM}(t) = A_C (\cos(2\pi f_C t))^2 (1 + m \cos(2\pi f_m t)) \]

\[ = \frac{A_C}{2} (1 + \cos(2\pi 2f_C t))(1 + m \cos(2\pi f_m t)) \]

\[ = \frac{A_C}{2} + \frac{A_C m}{2} \cos(2\pi f_m t) + \frac{A_C}{2} \cos(2\pi 2f_C t) \]

\[ + \frac{A_C m}{4} \cos(2\pi (2f_c - f_m) t) + \frac{A_C m}{4} \cos(2\pi (2f_c + f_m) t) \]
• Need to low pass filter – why?

• Another observation: the frequency component at the carrier frequency itself is not information-bearing.

• Why not just transmit the LSB and the USB, not the carrier?
  o Would save power

• ANS: We can, and it’s called AM – SC: Suppressed carrier
  o AM-SC can be demodulated by the synchronous detection approach (multiplying by the carrier cosine).
  o AM-SC cannot be demodulated by envelope detection.

• Question: what if the message is digital?
• Then we have what’s called Amplitude Shift Keying (ASK).
• Used in modems
• We can use a simpler model than traditional AM – instead of adding one to the message, simply multiply by zero or one. (You either have the carrier wave or you don’t)
$$x_{AM}(t) = A_C \cos(2\pi f_C t) \times [1 + m x_m(t)]$$
Amplitude Shift Keying

\[ x_{\text{ASK}}(t) = A_C \cos(2\pi f_C t) \times x_m(t) \]
FSK

- Another modulation technique used in modems is Frequency Shift Keying.

- Idea: Instead of having the message modulate the amplitude of the carrier, we modulate the frequency of the carrier.

- If the modulating signal is analog (e.g., voice) then this method is called frequency modulation (FM).
  
  - In this case, amplitude is constant. Information is carried in the “zero crossings” of the signal.
    - Robust to noise
    - Requires more bandwidth
  
  - We can also encode information in the phase (this is done with the GPS system… more shortly).

- If the message is binary, this method is called phase shift keying (PSK).
  
  - 0 is encoded as zero phase.
  - 1 is encoded as 180 degree phase shift in the cosine.
Frequency Shift Keying

\[ x_0(t) \]

\[ x_n(t) \]

\[ x_{FSK}(t) \]
Phase Shift Keying

![Graphs of phase shift keying signals](image-url)
Phase Shift Keying
Modulation Summary

Carrier

Information

ASK

FSK

PSK
• What are the advantages / disadvantages of these modulation schemes? What should we use in a modem? (modulator / demodulator) that allows digital information to be sent over phone line.

**ASK:**
- Simple, easy to design
- Loss of carrier signifies a zero – susceptible to noise

**FSK:**
- Signal always present
- Loss of carrier easy to detect
- Better noise immunity
- More complicated detection circuitry required
- Two frequencies required (one for 0, one for 1)
- Used, along with PSK, by Bluetooth in the iPhone

**PSK:**
- Same advantages as FSK, but only one frequency needed
- Transmission and detection circuitry more complicated than FSK

• Early modems: ASK
• “Modern” modems: combination of the above
• Let’s look at Quadrature Phase Shift Keying (QPSK)… it’s used by the iPhone to deliver 802.11b WiFi.

Standard PSK: 180 degree shift means data changes from 0 to 1 (1 bit)
PSK: zero degree shift means that data hasn’t changed.
PSK: this shift indicates that the message has changed from 1 to 0.
PSK: And back to 1 again…
QPSK: idea... why not use four different phase shifts to represent **TWO BITS**?
Need more advanced modem circuitry ... but the payoff is twice the information transfer.
Advanced modems: use even smaller phase differences and use ASK in addition to maximize information transfer.
Cellular Communications for Dummies

- Mobile phone history starts in the 1920’s in German trains for first class passengers!
- World War II: hand-held radio transceivers (which operate on principals that we’ve already discussed)
- First car phone in 1940’s due to Bell Labs. Such “portable” units weighed about 80 pounds(!)

- Cellular concept:
  - A multitude of base stations – cells.
  - Phones / cells can “handoff” in order for one phone to use a different cell tower as it moves through the network.
  - Frequencies (bandwidth) reused and shared
Wikipedia’s list of cellular network generations

(terms in **RED** will be developed in more detail in coming slides...)

**Analog Cellular (1G)**

- Advanced Mobile Phone System (AMPS) deployed in US in 1983.
- Unencrypted; easy to eavesdrop.
- Used **FDMA** (frequency domain multiple access)
- Analog FM modulation
- Frequency allocated by FCC on 824-849 MHz for downlink and 869-894 MHz for uplink traffic.
- RF bandwidth 30 kHz. The band can accommodate 832 duplex channels. Too bandwidth hungry...
Digital Cellular (2G)

- Digital transmission (what is transmitted are digital encodings, not simply modulated version of the analog voice signal...)
- Europeans went to GSM (Global system for mobile communications) using TDMA (time division multiple access)
- Americans fell in love with CDMA (code division multiple access)
- In Japan and China, folks like the Personal Handy-phone System (PHS) – a cordless phone that could move from cell to cell
  - Uses TDMA (time division multiple access)
  - Small cells, appropriate for dense urban areas
- 2G brought accommodated accessing media on mobile phones
- Ringtones!
- SMS (short message service) (1992)
- Smartphones! IBM Simon 1992-4
Mobile Broadband (3G)

- **Packet switching** (3G) vs. circuit switching (2G) for DATA
- More on packet switching in an upcoming module
- For now, an *analogy*...
- Circuit switching can be compared to a freight train – all the information travels together, in order, at the same speed.
- Packet switching is more like the postal system – you can put individual pages of a book in separate envelopes and mail and then reassemble. You can even mail some pages via UPS and Fedex which might take different routes and use vehicles of different speeds (airplanes, trucks, UAVs?!)
- Minimum speed for stationary or walking users: 2Mbit/s
  For moving vehicle: 348 kbit/s

Note: GSM has a CDMA capability in 3G through W-CDMA = wideband CDMA… more on CDMA shortly.
Native IP (4G)

- Streaming media kill 3G.
- Complete elimination of circuit switching; all communication uses packet switching
- 10X improvement over 3G in data rates
- Voice becomes media; treated just like data, images, and videos – it’s packetized!
- Standard: LTE = Long term evolution
CDMA v. GSM on the iPhone

- There are GSM versions and CDMA versions of the iPhone...
- Advantages (generally speaking) of CDMA:
  - Better, more consistent quality and coverage in rural areas (e.g., Loudon County)
  - High user capacity
- Disadvantages of CDMA / Advantages of GSM
  - CDMA has a lack of versatility: GSM is better at international roaming, switching SIM cards, using a variety of carriers/handsets
  - GSM is typically faster (not true in all cases)
CDMA?

What does it stand for?

- Code
- Division
- Multiple
- Access

Credit for CDMA help: Nick Waterman
FDMA

- Frequency
- Division
- Multiple
- Access
FDMA

(1G Cellular Networks)
TDMA

- Time
- Division
- Multiple
- Access
TDMA
F/TDMA

- Frequency and Time Division
- Multiple Access
F/TDMA

(2G Cellular Networks)
CDMA

- CODE
- Division
- Multiple
- Access

?
CDMA

All frequencies, all the time...
CDMA

(3G Cellular Networks)
Everyone transmits on top of each other?
Across the whole band?
At the same time?
YES.
With different codes,
and if you know the right code, you can receive just the person transmitting with that code.
Let’s compare to AM Radio…

**Voice Spectrum**
Voice, Carrier

… and mix ...
AM
Let’s do a similar process with CDMA – it has a wide bandwidth spreading code:

*Data Signal + Code*

... and mix ...
CDMA

… to make really wideband CDMA spread spectrum signal

… but we can also turn the power down ...
… **below** the noise floor!
… and still be heard!
Trust me. We'll prove it later.
Review: Multiplication

\[
\begin{bmatrix}
1 & 1 & -1 & -1 \\
X & X & X & X \\
1 & -1 & 1 & -1 \\
\end{bmatrix}
\]

Inner product of two vectors \( x, y \)

\[
\langle x, y \rangle = \sum_i x_i y_i
\]

Example: \( x = [+1, -1, +1, -1] \), \( y = [+1, +1, -1, -1] \), \( z = [+1, +1, +1, -1] \)

\[
\langle x, y \rangle = 0, \quad \langle x, z \rangle = 2, \quad \langle x, y + z \rangle = 2
\]

\[
\langle x, y + z \rangle = \langle x, y \rangle + \langle x, z \rangle = 0 + 2 = 2
\]

\[
\langle x, x \rangle = 4, \quad \langle x, -x \rangle = -4
\]
The longer period is called the bit period and the shorter period is called the chip period. There are $N = 8$ chips per bit here.

$$c_A = [+1, -1, -1, -1, +1, -1, +1, +1]$$

User $A$:
- Instead of 1 send $c_A$
- Instead of 0 send $-c_A$
**CDMA example**

Low-Bandwidth Signal:

\[1\ 1\ -1\ 1\ -1\ -1\]

High-Bandwidth Spreading Code:

\[1\ -1\ -1\ -1\ 1\ 1\ -1\ -1\ -1\ 1\ 1\ 1\ -1\ -1\ 1\ 1\ 1\ -1\ -1\ -1\ 1\]

Mix is a simple multiply

\[1\ -1\ -1\ 1\ 1\ -1\ -1\ 1\ 1\ 1\ -1\ -1\ 1\ 1\ 1\ -1\ -1\ -1\ 1\]

… and transmit.

Need to send: \(1, 1, -1, 1, -1, -1\)

We send: \(c_A, c_A, -c_A, c_A, -c_A, -c_A\)
**CDMA example**

To Decode / Receive, take the signal:

Received sequence: $c_A, c_A, -c_A, c_A, -c_A, -c_A$

Multiply by: $c_A, c_A, c_A, c_A, c_A, c_A$

Result: 8,8,-8,8,-8,-8

Decoded bits: 1,1,-1,1,-1,-1
What if we use the wrong code?

Take the same signal:

\[
\begin{align*}
\text{Received sequence: } & c_A, c_A, -c_A, c_A, -c_A, -c_A \\
\text{Multiply by the wrong Spreading Code: } & c', c', c', c', c'
\end{align*}
\]

\[
\text{... for example, let's just shift the same code left a bit:}
\]

Received sequence: \(c_A, c_A, -c_A, c_A, -c_A, -c_A\)

Multiply by: \(c', c', c', c', c'\)

\[
\begin{align*}
c_A &= [+1, -1, -1, -1, +1, -1, +1, +1] \\
c' &= [-1, -1, -1, +1, -1, +1, +1, +1]
\end{align*}
\]

Result: ??
What if we use the wrong code?

Take the same signal:

\[c_A, c_A, -c_A, c_A, -c_A, -c_A\]

Multiply by the wrong Spreading Code:

\[c'_A, c'_A, c'_A, c'_A, c'_A, c'_A\]

\[
\begin{align*}
1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 \\
1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 \\
1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 \\
1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 \\
\end{align*}
\]

\[
\begin{align*}
-1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 \\
-1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 \\
-1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 \\
-1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 \\
\end{align*}
\]

\[
\begin{align*}
\ldots & \text{you get...} \\
\ldots & \text{which clearly hasn't recovered the original signal.} \\
\text{Using wrong code is like being off-frequency.}
\end{align*}
\]

Received sequence: \(c_A, c_A, -c_A, c_A, -c_A, -c_A\)

Multiply by: \(c', c', c', c', c', c'\)

\[
\begin{align*}
c_A &= [+1, -1, -1, -1, +1, -1, +1, +1] \\
c' &= [-1, -1, -1, +1, -1, +1, +1, +1]
\end{align*}
\]

Result: first bit: -1+1+1-1-1+1+1 = 0

Could also get some other number close to zero (but not 8 or -8)
CDMA in detail

- Suppose code length is $N$ chips
- User A has code $c_A$ and user B has code $c_B$
- We choose $c_A$ and $c_B$ such that $\langle c_A, c_B \rangle = 0$
- Both users send us data at the same time
- User A sends the data +1 as $c_A$ and -1 as $-c_A$
- User B sends the data -1 as $-c_B$ and -1 as $-c_B$
- Some noise is added by the channel: $n$

- At the receiver, we receive $c_A - c_B + n$
- But we don’t know what this signal is so at the receiver let’s write it as $s = u_A + u_B + n$, where
  \[ u_A = c_A \text{ or } -c_A \]
  \[ u_B = c_B \text{ or } -c_B \]

  We don’t know which one, and would like to find out.

- Decode for user A: compute $\langle s, c_A \rangle$
  \[ \langle s, c_A \rangle = \langle u_A, c_A \rangle + \langle u_B, c_A \rangle + \langle n, c_A \rangle \]
  - $\langle u_B, c_A \rangle = 0$ (why?)
  - $\langle n, c_A \rangle \approx 0$ (try a few examples)
• Then

\[ \langle s, c_A \rangle \approx \langle u_A, c_A \rangle = \begin{cases} N & \text{if } u_A = c_A \\ -N & \text{if } u_A = -c_A \end{cases} \]

• So for decoding, compute \( \langle s, c_A \rangle \)
  - If \( \langle s, c_A \rangle > 0 \) declare +1
  - If \( \langle s, c_A \rangle < 0 \) declare -1

• Example:

\[ c_A = [+1, -1, +1, -1, +1, -1, +1, -1, +1] \]
\[ c_B = [+1, -1, -1, +1, -1, +1, -1, +1, +1] \]

Suppose user A sends 1, user B sends -1, and the noise vector is
\[ n = [0, +1, 0, +1, -1, -1, -1, 0] \]

The received vector is
\[ s = [0, 1, 2, 1, -3, 1, -3, 0] \]

At the receiver, compute
\[ \langle s, c_A \rangle = 7 \rightarrow 1 was sent by A \]
\[ \langle s, c_B \rangle = -11 \rightarrow -1 was sent by B \]
Audience Participation

- **LEFT** side of room:
  - Take some “data” (pick a letter)
  - Multiply by Spreading Code A
  - "Transmit" CDMA to me

- **RIGHT** side of room:
  - Take some “data” (pick a letter)
  - Multiply by Spreading Code B
  - "Transmit" CDMA to me

2 volunteers will make some **NOISE** (-1, 0, +1)

We will add **LEFT**+**RIGHT**+**NOISE** to see what might be received on the band
Audience Participation

- LEFT side of room:
  - Multiply by Spreading Code B
  - “Receive” CDMA from RIGHT

- RIGHT side of room:
  - Multiply by Spreading Code A
  - “Receive” CDMA from LEFT

... and with some luck, it'll work!

We will add \( \text{LEFT} + \text{RIGHT} + \text{NOISE} \) to see what might be received

\[
c_A = [+1, -1, +1, -1, -1, +1, -1, +1, +1]
\]
\[
c_B = [+1, -1, -1, -1, +1, -1, +1, +1, +1]
\]
First, pick a letter.

<table>
<thead>
<tr>
<th>Letter</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>A</td>
<td>1 1 1 1 1</td>
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<tr>
<td>B</td>
<td>1 1 1 1 -1</td>
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<tr>
<td>C</td>
<td>1 1 1 -1 1</td>
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<tr>
<td>D</td>
<td>1 1 1 -1 -1</td>
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<td>Z</td>
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### Example TX

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</tbody>
</table>

| = | = | = | = | = | = | = | = | = | = | = | = | = | = | = |

CDMA
### Example TX

<table>
<thead>
<tr>
<th>Data</th>
<th>1</th>
<th>-1</th>
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</thead>
<tbody>
<tr>
<td>x</td>
<td>x x x x x x x x x x x x x x x x x</td>
<td></td>
</tr>
<tr>
<td>Spreading Code</td>
<td>1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1</td>
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<td>= = = = = = = = = = = = = = =</td>
<td></td>
</tr>
<tr>
<td>CDMA</td>
<td>1 -1 1 -1 1 -1 1 -1 1 1 -1</td>
<td>-1</td>
</tr>
</tbody>
</table>
\[ A + B + \text{Noise} = \text{Band} \]

| CDMA A | 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 |
| CDMA B | 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 |
| CMDA  | + + + + + + + + + + + + + + + + + |
| NOISE | 3 2 3 2 5 5 3 2 5 4 5 4 2 4 5 5 |
| =     | = = = = = = = = = = = = = = = = = |
| BAND  | 5 0 3 2 3 7 3 2 3 6 5 4 4 2 5 5 |
# Example RX

<table>
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<tr>
<th>BAND</th>
<th>5 0 3 2 3 7 3 2 3 6 5 4 4 2 5 5</th>
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<td>Add these</td>
<td>+  +</td>
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<tr>
<td>Total</td>
<td>9  -3</td>
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<tr>
<td>1 or -1?</td>
<td>1  -1</td>
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</tbody>
</table>
### Find The Letter.

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Networks

- How does the iPhone communicate with other devices over the Internet? (First, let’s discuss the difference between **circuit switched** networks & **packet switched** networks like the Internet)

- Problem: how to link information devices / systems together in a network to facilitate
  - Distributed computing (resource sharing)
  - Information exchange
  - Commerce
  - Reliability and backup

- Many methods possible – broad outlines of basic principles can be determined by considering two types of traffic…
  - Voice
  - Data
- Characteristics of voice transmission
  - Continuous
  - Synchronous – information must be reconstructed in real-time and in order (order and rate of transmission must equal order and rate of reception)
  - Fairly low bandwidth required, but the bandwidth must be available during the entire length of the exchange

- Characteristics of data transmission (internet, email, etc.)
  - Bursty rather than continuous
  - Asynchronous – order of transmission is irrelevant, as long as data are reassembled properly
  - Need high bandwidth to handle peak traffic, but this bandwidth is not use continuously

- Original large scale information network is the public switched telephone network (PSTN)
  - Designed to handle voice traffic
  - Not ideally suited to data traffic
  - Example of a circuit switched network
• Idea behind a circuit switched network is a definite, identifiable channel that connects the two end-users. The channel remains unbroken for the duration of the call.
• Originally, the circuit consisted entirely of copper wires and amplifiers and switches.
  o A circuit in this case is a complete path over which electrical current can flow.
  o Dialing the phone number starts the process that establishes the circuit.
  o Once established, others cannot use that channel.
  o So, circuit switching is like a system of tubes and valves.
  o Switches are necessary to route information from source to destination.
• First telephones used patch cords to accomplish this routing. (Think *Mad Men.*)

• These were replaced with electromagnetic relays.

• So with the PSTN, the number of users is limited to the number of available channels.

• Circuit switching can guarantee a high quality of service (QOS).
• In this network, bandwidth and SNR are controlled.

• Latency is determined by length.

• Circuit switched networks are ill-suited to data transmission
  o Bursty nature of data requires high bandwidth for short periods of time, and no or small bandwidth for the rest of the time.
  o Circuit switched network reserves a channel, including the associated bandwidth, for the duration of the call
    ▪ Expensive and inefficient
Packet Switching

- Idea: break information up into separate, distinct packets.

- Every packet has an address that specifies the destination.

- Packets are launched without regard to the path.
  - Path is not determined beforehand (as with PSTN).

- At the destination, the packets are reassembled.

- Packet switching allows sharing of the channels and the associated bandwidth.

- Packets can be dynamically routed – to avoid bottlenecks and regions of high traffic.

Analogy: Circuit switching can be compared to a freight train – all the information travels together, in order, at the same speed. Packet switching is more like the postal system – you can put individual pages of a book in separate envelopes and mail and then reassemble.
• Important point: QOS cannot be guaranteed for packet switched network!
  o Latency depends upon path, which can be circuitous.

_EX_: Let’s test connection to computer in Japan…

_C:\WINDOWS>_ping cc.mech.tohoku.ac.jp

Pinging cc.mech.tohoku.ac.jp [130.34.54.4] with 32 bytes of data:

Reply from 130.34.54.4: bytes=32 time=426ms TTL=235
Reply from 130.34.54.4: bytes=32 time=421ms TTL=235
Reply from 130.34.54.4: bytes=32 time=395ms TTL=235
Reply from 130.34.54.4: bytes=32 time=394ms TTL=235

Ping statistics for 130.34.54.4:
  Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
Approximate round trip times in milli-seconds:
  Minimum = 394ms, Maximum = 426ms, Average = 409ms

Let’s try again…
C:\WINDOWS>ping cc.mech.tohoku.ac.jp

Pinging cc.mech.tohoku.ac.jp [130.34.54.4] with 32 bytes of data:

Request timed out.
Reply from 130.34.54.4: bytes=32 time=393ms TTL=235
Reply from 130.34.54.4: bytes=32 time=405ms TTL=235
Reply from 130.34.54.4: bytes=32 time=438ms TTL=235

Ping statistics for 130.34.54.4:
   Packets: Sent = 4, Received = 3, Lost = 1 (25% loss),
Approximate round trip times in milli-seconds:
   Minimum = 393ms, Maximum = 438ms, Average = 309ms

• Can we examine the route?
traceroute cc.mech.tohoku.ac.jp
trying to get source for cc.mech.tohoku.ac.jp
source should be 128.143.2.33
traceroute to cc.mech.tohoku.ac.jp (130.34.54.4) from 128.143.2.33
(128.143.2.33), 30 hops max
outgoing MTU = 1500
1  cisco-router1.itc.Virginia.EDU (128.143.2.2)  7 ms  1 ms  1 ms
2  uva-internet.acc.Virginia.EDU (128.143.99.1)  3 ms  2 ms  3 ms
3  abilene-uva.misc.Virginia.EDU (192.35.48.42) 10 ms 10 ms 10 ms
4  clev-nycm.abilene.ucaid.edu (198.32.8.29) 22 ms 22 ms 22 ms
5  ipls-clev.abilene.ucaid.edu (198.32.8.25) 30 ms 28 ms 28 ms
6  kscy-ipls.abilene.ucaid.edu (198.32.8.5)  37 ms 40 ms 37 ms
7  dnvr-kscy.abilene.ucaid.edu (198.32.8.13) 48 ms 48 ms 48 ms
8  scrm-dnvr.abilene.ucaid.edu (198.32.8.1)  70 ms 70 ms 69 ms
9  losa-scrm.abilene.ucaid.edu (198.32.8.18) 77 ms 77 ms 77 ms
10  abilene-A1-1-0-1.sinet.ad.jp (150.99.200.205) 78 ms 78 ms 77 ms
11  nacsis-gate5-A0-0-1-1.sinet.ad.jp (150.99.200.193) 194 ms 194 ms 194 ms
12  nacsis-10-GE2-0.sinet.ad.jp (150.99.99.2) 206 ms 206 ms 205 ms
13  tohoku-10-A4-0-1.sinet.ad.jp (150.99.148.8) 211 ms 211 ms 211 ms
14  tohoku-1-A0-1-0-1.sinet.ad.jp (150.99.198.81) 213 ms 221 ms 216 ms
15  tohoku.gw.sinet.ad.jp (150.99.61.3) 212 ms 212 ms 214 ms
16  sasaya.net.tohoku.ac.jp (202.211.0.3) 214 ms 213 ms 213 ms
17  togatta.net.tohoku.ac.jp (130.34.11.122) 214 ms 213 ms 214 ms
18  mc0800.net.tohoku.ac.jp (130.34.36.253) 217 ms 230 ms 213 ms
19  130.34.39.74 (130.34.39.74) 217 ms 221 ms 216 ms
20  prog-gw.mech.tohoku.ac.jp (130.34.54.4) 216 ms * 215 ms
(*try http://visualroute.visualware.com)
Report for lmt.unine.ch [130.125.1.29]

Analysis: 'lmt.unine.ch' was found in 15 hops (TTL=114). Connections to HTTP port 80 are being rejected.

<table>
<thead>
<tr>
<th>Hop</th>
<th>IP Address</th>
<th>Node Name</th>
<th>Location</th>
<th>Tzono</th>
<th>hrs</th>
<th>Graph</th>
<th>Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>161.50.176.16</td>
<td>wn10115.4.adt</td>
<td>Dulles, VA, USA</td>
<td>-5.3</td>
<td>0</td>
<td></td>
<td>Verio, Inc.</td>
</tr>
<tr>
<td>1</td>
<td>161.58.176.12</td>
<td>Englewood, CO 80112</td>
<td>Englewood, CO 80112</td>
<td>0</td>
<td>0</td>
<td></td>
<td>Verio, Inc.</td>
</tr>
<tr>
<td>2</td>
<td>161.58.166.14</td>
<td>Sterling, VA, USA</td>
<td>3-1-0 r10n sl</td>
<td>0</td>
<td>0</td>
<td></td>
<td>Verio, Inc.</td>
</tr>
<tr>
<td>3</td>
<td>123.250.1.157</td>
<td>Mclean, VA, USA</td>
<td>Mclean, VA, USA</td>
<td>-5.3</td>
<td>0</td>
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</tr>
<tr>
<td>4</td>
<td>123.250.2.249</td>
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</tr>
<tr>
<td>5</td>
<td>123.250.2.245</td>
<td>Palo Alto, CA USA</td>
<td>-2.1 78</td>
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<td></td>
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</tr>
<tr>
<td>6</td>
<td>193.32.176.12</td>
<td>Marin del Rey, CA 90295</td>
<td>4-4-0-0-7</td>
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<tr>
<td>7</td>
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<td>io0nyc-015-sa</td>
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<td>10</td>
<td>171</td>
<td></td>
<td>Exchange Point</td>
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<tr>
<td>8</td>
<td>164.128.233.9</td>
<td>swnlx-1-f1-0-s</td>
<td>(Switzerland)</td>
<td>10</td>
<td>174</td>
<td></td>
<td>Internet Service</td>
</tr>
<tr>
<td>9</td>
<td>192.65.33.25</td>
<td>swicel1-p6-1-i</td>
<td>(Switzerland)</td>
<td>10</td>
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<tr>
<td>10</td>
<td>133.39.33.8</td>
<td>swicel1-xa-0-0-c</td>
<td>(Switzerland)</td>
<td>10</td>
<td>265</td>
<td></td>
<td>SWITCH Telei</td>
</tr>
<tr>
<td>11</td>
<td>133.39.33.7</td>
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<tr>
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<tr>
<td>13</td>
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<td>(Switzerland)</td>
<td>10</td>
<td>268</td>
<td></td>
<td>University of Ne</td>
</tr>
</tbody>
</table>

4/14/01  265 ms
Let’s look at AT&T IP backbone network *bbone2001.pdf

- WAN: Wide area network
  - Along with others (MCI, Sprint, PSI, UUNET) they comprise the Internet.

- Smaller networks are LANs (local area networks).
Packet Structure

- The information in the packet must be standardized so that everyone on the network can interpret it.

### Packet Structure

<table>
<thead>
<tr>
<th>Address</th>
<th>Data Length</th>
<th>Tag</th>
<th>Data</th>
<th>CRC</th>
</tr>
</thead>
</table>

- Similar to phone number (i.e., access code, country code, area code, local exchange, extension)

- **Data length**: how many bytes in data section?
  - Since every packet must have non-data overhead, we want long data blocks.
  - But large packets tie up the network, are sometimes wasteful, and increase probability of error in a packet.
  - Typically, packets are 46-1500 bytes in length.
  - Larger data blocks are broken into multiple packets.
• **Tag** – a number that indexes the data. (usually one byte, so it can index up to 256 packets)

• **Data** – the actual information

• **CRC** – cyclic redundancy check
  
  o Packet level error correction
  
  o Simple version: Add up 1’s in data. Take mod 256. Do the same at the receiver to check.

  **Better way: CRC**

  **Background:**

  • A binary sequence can be written as a polynomial:

    $1101 \leftrightarrow 1 \cdot x^3 + 1 \cdot x^2 + 0 \cdot x + 1 \cdot 1 = x^3 + x^2 + 1$

    $0110 \leftrightarrow x^2 + x$

  • The computation of the CRC is based on two principles:

    o mod 2 arithmetic
    o polynomial division

  • mod 2 arithmetic: Arithmetic over the field of integers mod 2 is simply arithmetic on single bit binary numbers with all carries
(overflows) ignored. So $1 + 1 = 0$ and so does $1 - 1$. Addition and subtraction are equivalent in this form of arithmetic.

- $1101 + 0110 = 1011$
- $x^3 + x^2 + 1 + x^2 + x = x^3 + x + 1$

- polynomial division: division of polynomials using modulo 2 arithmetic:
  - $\frac{x^3+x^2+1}{x^2+x} = x + \frac{1}{x^2+x}$
  - Quotient = $x$
  - Remainder = 1

**CRC**

![CRC Diagram]

Need a polynomial $P(x)$ of degree $n$

- Called the “generator polynomial.”
- Equivalent to a binary number of length $n+1$
- Get the raw binary message \( M \). Call the polynomial \( M(x) \)

- Left shift \( M \) by \( n \) bits : multiply \( M(x) \) by \( x^n \)
  
  \[
  M(x) \leftrightarrow m_k \ m_{k-1} \ldots m_0
  \]
  
  \[
  M(x)x^n \leftrightarrow m_k \ m_{k-1} \ldots m_000\ldots00
  \]

- Find the remainder of \( M(x)x^n/P(x) \). The remainder in binary is the \( n \)-bit CRC.
  
  \[
  x^nM(x) = Q(x)P(x) + R(x)
  \]
  
  \[
  CRC = R(x) \leftrightarrow r_n \ r_{n-1} \ldots r_0
  \]

- Append the CRC to the raw message. Transmit
  
  \[
  T(x) = M(x)x^n + R(x) \leftrightarrow m_k \ m_{k-1} \ldots m_0 \ r_n\ldots r_0
  \]

- At the receiver, divide the received string of bits by \( P(x) \). Check the remainder.
  
  - If zero, no error is detected.
  
  - If not zero, then we have an error. Retransmit.

A CRC of degree \( n \) that does not have \( x \) as a factor can detect all burst errors of length at most \( n \).
Mod P(x) means remainder of division by P(x)

Bob receives $S(x) = T(x) + E(x)$. $E(x)$ represents the error.

**Claim:** If $E(x) = 0$ (no error), the remainder of the received string by $P(x)$ is zero.

- We know
  $$T(x) = x^n M(x) + R(x)$$
- Since addition and subtraction are identical
  $$T(x) = x^n M(x) - R(x)$$
- But remember that
  $$x^n M(x) = Q(x) P(x) + R(x)$$
- So we have
  $$T(x) = Q(x) P(x)$$
- So the transmitted polynomial (with $R(x)$ appended) will be divisible by $P(x)$. 

5.95
When is an error undetected?

- If the remainder of \( S(x) = T(x) + E(x) \) by \( P(x) \) is zero but \( E(x) \) is not zero, we have an undetected error.

\[
S(x) \mod P(x) = T(x) \mod P(x) + E(x) \mod P(x) = 0 + E(x) \mod P(x)
\]

- Undetected error if \( E(x) \mod P(x) = 0 \).

- Can be shown that CRC of degree \( n \) can correct burst errors of length up to \( n \).
• An example:
  
  • Suppose we want to send the message 11010111 using the CRC with the polynomial $x^3 + x^2 + 1$ as our generator $P(x)$.
  • The message corresponds to the polynomial:
    
    $$x^7 + x^6 + x^4 + x^2 + x + 1$$
  
  • Given $P(x)$ is of degree 3, we need to multiply this polynomial by $x^3$ and then divide the result by $P(x)$.

\[
x^7 + \quad x^2 + 1 \\
\frac{x^3 + x^2 + 1}{x^{10} + x^9 + x^7 + x^5 + x^4 + x^3}
\]

\[
x^{10} + x^9 + x^7
\]

\[
x^5 + x^4 + x^3
\]

\[
x^5 + x^4 + x^2
\]

\[
x^3 + x^2 + 1
\]

\[
x^3 + x^2 + 1
\]

(Example credit: Johns Hopkins U.)
The remainder is "1". So, the parity bits added in this case would be 001.
The message sent: 11010111001

Continuing the example:

- If we receive 11010111001:
  \[ x^{10} + x^9 + x^4 + x^3 + 1 = (x^7 + x^2 + 1)(x^3 + x^2 + 1) + 0 \]
  - Remainder is zero \(\Rightarrow\) no error

- If we receive 11000011001 instead of 11010111001.
  \[ x^{10} + x^9 + x^4 + x^3 + 1 = (x^7 + x^4 + x^3 + x^2 + x + 1)(x^3 + x^2 + 1) + x \]
  - Remainder is \(x\) \(\Rightarrow\) error

A 32 bit CRC is standard, such as CRC32 = \(x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1\)
Protocols

- The design of the network involves many decisions, which together form a protocol – a set of rules governing communication.

- Common assumptions for LANs
  - \( N \) independent stations that transmit packets
  - Only one channel is available.
  - Two or more packets transmitted simultaneously generate a collision.
    - After collision, packets must be retransmitted.
  - Packet transmission can begin at any time.
  - Stations can “sense” before transmitting or not.
TCP/IP Protocol

• A widely used protocol is the transmission control protocol / internet protocol.
  o Stations can “sense” before transmitting or not.
  o The internet is of course a set of networks (Arpanet, commercial networks, LANs, etc.)
  o All use TCP/IP to connect.

• TCP/IP has associated applications such as:
  o File transfer (FTP) – copy files from one system to the other
  o Remote login (Telnet) – use a local computer to send instructions to another computer in real-time
  o Computer mail – send messages
  o Hypertext transfer protocol (HTTP) – send text, images, sound, video, etc.
IP Addresses

- To find a computer on the web, we use a domain name (DNS: domain name system).

EX: eeultra.ee.virginia.edu
Address is 128.143.10.69

- Computers on the “standard” UVA network begin with 128.143
  - 10 (in the above) indicates a subnet
  - 69 indicates the individual computer
  - There are also other UVA IP addresses (not starting with 128.143) for dorms, hospital, wireless networks, etc.

- Most individual computers are dynamically addressed – IP addresses are reused as computers connect and disconnect from the network.

- To get the IP address of your iPhone: Press to select Wi-Fi from the Settings menu. Press to select your network if it is not already selected. Then next to your network name press the blue circle with the arrow in it.